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Parameter Estimation of Spacecraft Nutation Growth Model

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ABSTRACT

Modeling fuel slosh effects accurately and completely on spinning spacecraft has been a long standing concern within the aerospace community. Gyroscopic stiffness is obtained by spinning spacecraft as it is launched from one of the upper stages before it is placed in orbit. Unbalances in the spacecraft causes it to precess (wobble). The oscillatory motions are caused in the fuel due to this precession. This phenomenon is called "fuel slosh" and the dynamic forces induced could adversely affect the stability and control of a spacecraft that spins about one of its minor moments of inertia axes. An equivalent mechanical model of fuel slosh is developed using springs and dampers that are connected to the rigid fuel tank. The stiffness and damping coefficients are the parameters that need to be identified in the fuel slosh mechanical model. This in turn is used in the spacecraft model to estimate the Nutation Time Constant (NTC) for the spacecraft. The experimental values needed for the identification of the model parameters are obtained from experiments conducted at Southwest Research Institute using the Spinning Slosh Test Rig (SSTR). The research focus is on developing models of different complexity and estimating the model parameters that will ultimately provide a more realistic Nutation Time Constant obtained through simulation.

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1. INTRODUCTION

Fuel slosh in spacecrafts has been a long standing concern within the aerospace community and has been a source of dynamics and control problems [1]. Quantifying the fuel slosh effects using equations is not feasible during the initial phases of design. Simplified models will greatly help to reduce computational time and design costs [2].

Liquid oscillations in spinning tanks have been studied in the past. Liquid oscillations in spinning fuel tanks produce very different response characteristics compared to those of non-spinning fuel tanks [3].

An energy sink model was originally developed by Thomson [4] to include the effects of small, passive sources of energy dissipation. This model does not work well for spacecraft fuel slosh energy dissipation due to the fact that fuel mass is a large fraction of the total mass of the spacecraft.

A homogeneous vortex model of liquid motions in spinning tanks and an equivalent mechanical model was developed by Dodge et al., [5]. An approximate theory of oscillations that predicts the characteristics of the dominant inertial wave oscillation and the forces and moments on the tank are described. According to Dodge et al., the pendulum model simulates a motion that does not involve an oscillation of the center of mass, it is not a valid model of inertial wave oscillations. Weihs and Dodge [6] illustrate that the free surface effects can be ignored when the liquid depth is small.

A 3-D pendulum model was proposed by Green et al., [7]. There was evidence of liquid resonance from the experimental data. The resonance closely was tied to the tangential torque and to a lesser degree to the radial torque, and little or no resonance in the force measurements. Green et al., proposed a rotary oscillator concept to simulate the torque resonance in tangential and radial directions. This rotary oscillator model was superimposed on the pendulum model to provide the overall response of liquid oscillation in the tank.

Hence, there is a need to develop a model that is capable of accounting for all motions of the liquid within the tank. In this research, a more generalized 3-D Rotor Model is proposed that will account for all the liquid oscillation effects through springs and dampers.

2. SCOPE OF RESEARCH

The scope of this research is to provide an alternate approach to obtain the Nutation Time Constant (NTC) by developing mechanical models of various complexity through springs and dampers that simulate the fuel motion inside the spinning spacecraft fuel tank. The model parameters will be identified using the experimental values for forces and torques obtained by conducting experiments using the Spinning Slosh Test Rig. The “goodness of fit” will be assessed for the identified parameters.

3. PROBLEM DEFINITION

The experimental set-up of the Spinning Slosh Test Rig (SSTR) is shown in Figure 1. The SSSTR can subject a test tank to a realistic nutation motion, in which the spin rate and the nutation frequency can be

varied independently, with the spin creating a centrifugal acceleration large enough to ensure that the configuration of the bladder and liquid in the tank is nearly identical to zero-g configuration. A complete description of the actual tests, data acquisition and analyses of data is provided by Green, et al., [7]. The fuel motion is simulated using models with various parameters (inertia, springs, dampers, etc.) and the problem reduces to a parameter estimation problem to match the experimental results obtained from SSTR.

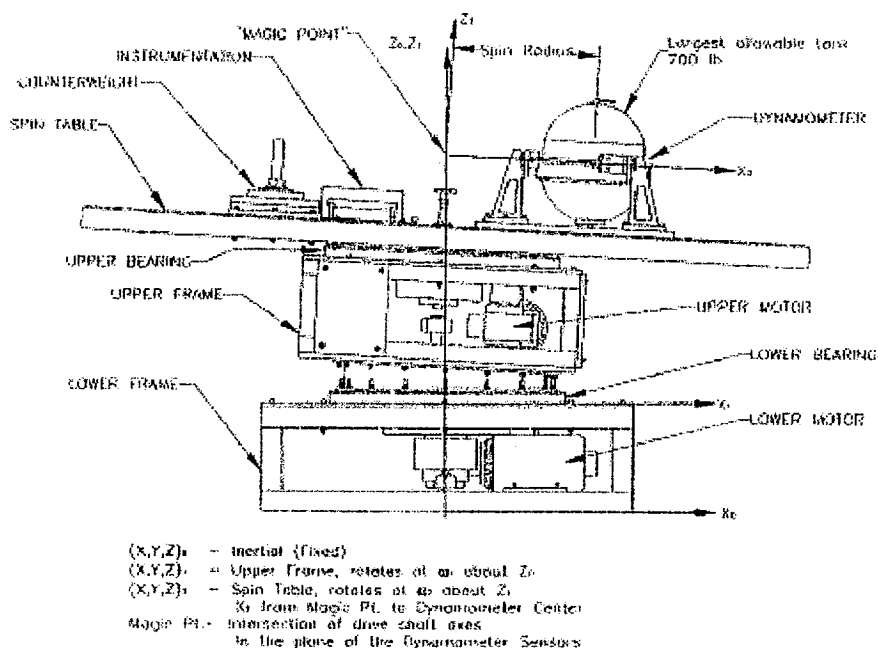


Figure 1. Schematic diagram of Spinning Slosh Test Rig (SSTR)

4. METHOD OF APPROACH

A 3-D Rotor Model of SSTR is developed using SimMechanics software [8,9] and shown in Figure 2. This model has flexibility to include different parameters (inertia of rotor, translational and rotational stiffnesses and dampers in the three mutually perpendicular directions, offsets, etc.) in the parametric estimation process. The complexity of the Rotor Model depends on the parameters included in the estimation process. It is imperative that more parameters will provide better response characteristics closer to reality. The block diagram of the system identification procedure is illustrated in Figure 3. The identified parameters are input into the spacecraft model to obtain the Nutation Time Constant.

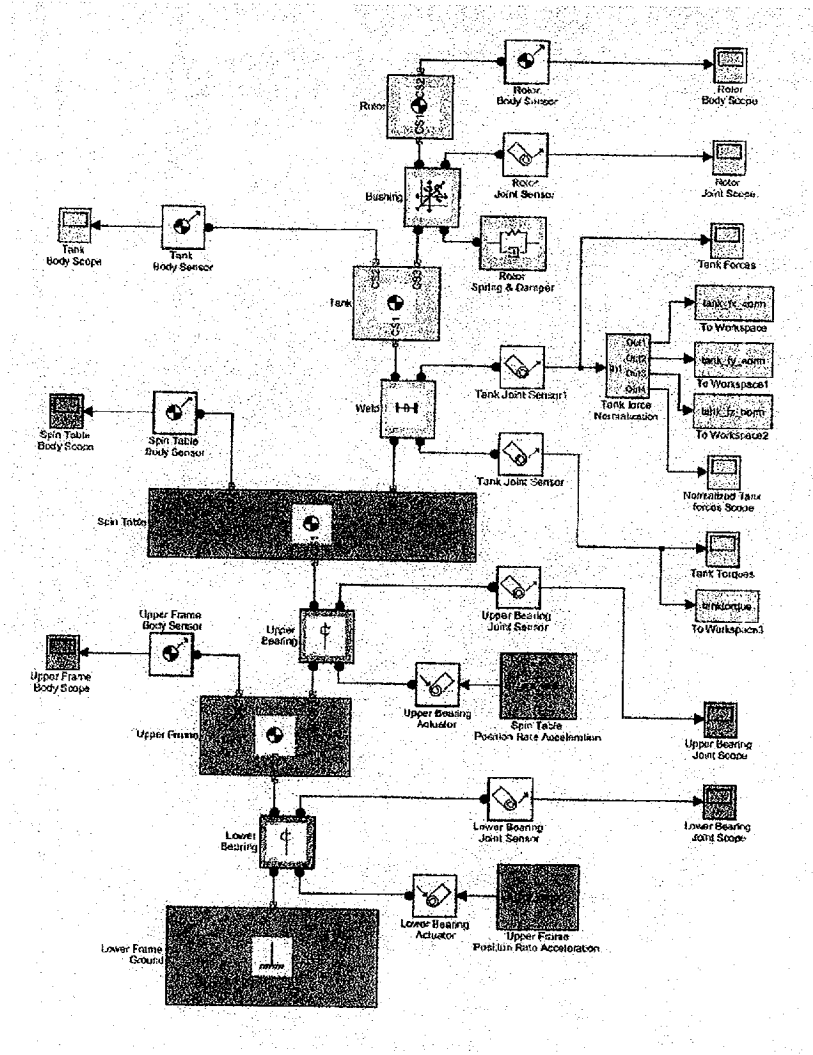


Figure 2. 3-D Rotor Model developed using SimMechanics software

5. OPTIMIZATION CONCEPT

The parametric estimation problem reduces to an optimization problem of minimizing the residual which is the sum of the squares of the difference between the experimental and model response. This can be put in the mathematical form as:

Minimize

$$\text{Residual } R = \sum (\text{Experimental Response} - \text{Model Response})^2$$

This minimization of residual is performed using a nonlinear least squares algorithm “LSQNONLIN” available in Optimization Tool Box.